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Preliminary Testing of the Creams Erosion Sub-Model with Field Data from Silsoe, Bedfordshire, England

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PRELIMINARY TESTING OF THE CREAMS EROSION SUB-MODEL WITH FIELD DATA FROM SILSOE, BEDFORDSHIRE, ENGLAND

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PREFACE

Land resources and associated phenomena are among the principle fields of interest for the Resources and Environment Area of IIASA. Soil erosion is one of the unfavorable processes deteriorating natural fertility of the land and polluting water bodies. From its beginning, the REN Task 3 on "Environmental Problems of Agriculture" has kept an interest in soil erosion as is proved by our publications (WP-79-61, CP-80-10, WP-80-129). There are plans to focus our investigation in 1981 on systems aspects of soil erosion.

This paper has a clear logical connection with the paper of G. Foster et al. (CP-80-10): G. Foster et al. give a description of the model tested by R.P.C. Morgan. This work became possible as a part of the activity supported both by the organizations within the U.K. and by IIASA. A part of IIASA's expenses came from the US Industry Fund known as "International Cooperation in Systems Analysis Research" (ICSAR Project No. 7). The main goal of the project was to transfer a non-point source pollution model, which was developed in the USA, to IIASA and, through IIASA, to the member countries.

Prof. Genady Golubev
Task Leader

ABSTRACT

A preliminary investigation of the applicability of the CREAMS non-point source pollution model to British conditions was carried out by testing the erosion sub-model using field data from mid-Bedfordshire, England. With a sample of 31 storms a correlation coefficient of r = 0.87 was obtained between predicted and observed values. This result is better than has been achieved using other models to predict erosion in mid-Bedfordshire and compares well with the results obtained by users of the model in the U.S.A. Three strategies are discussed and the results of the best one presented for operating the sub-model on a hillside where the overland flow and rill flow paths are approximately parallel. The results imply that the channel flow component may need to be redefined to include as channels convergent flow paths within the overland flow.

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R. P. C. Morgan

INTRODUCTION

The pollution of water resources by sediments, nutrients and pesticides is a priority concern of the various bodies charged with water management in many countries. In the United Kingdom investigations of pollution and water quality are carried out by many organisations including Regional Water Authorities, the Water Pollution Research Laboratory, the Ministry of Agriculture, Fisheries and Food, and the Institute of Hydrology (Department of the Environment, 1973). Although the techniques for monitoring and predicting point sources of pollution, e.g. factory discharges, are reasonably well established, little attention has been paid in the U.K. to the evaluation of non-point source pollution, e.g. the input of sediment and chemicals to a river through surface runoff and subsurface water movement on hillsides. This topic has been much researched in the U.S.A., however, where procedures for evaluation have advanced to the development of a field scale model for predicting runoff and its sediment and solute concentrations. This paper describes preliminary trials of the applicability to British conditions of part of that model, namely the erosion sub-model.

THE CREAMS MODEL

CREAMS is a field scale model for assessing chemicals, runoff and erosion from agricultural management systems. It has been developed in the U.S.A. from research carried out by the U.S. Department of Agriculture, Science and Education Administration (Agricultural Research). The model combines three sub-models: hydrology, erosion and chemicals. These predict, in turn, the volume of runoff, the rate of soil loss and the output of dissolved and adsorbed chemicals. The background to the model is discussed by Knisel (1978) and the details are described in Knisel (1980).

The erosion sub-model reflects the current approaches to erosion modelling being developed in the U.S.A. (Meyer and Wischmeier, 1969; Foster and Meyer, 1972; Meyer, Foster and Römkens, 1975). The sub-model is thus partly physically-based and partly empirical. Erosion is viewed as a two-phase process comprising the detachment of soil particles from the soil mass and their transport downslope. Raindrop impact and overland flow are the main agents of detachment and transport on the interrill areas of a hillside and concentrated flow is the main agent in rills. The sub-model combines the rills and interrill areas, calculates the rate of detachment of soil particles and compares this with the capacity to transport them. Where the transport capacity is insufficient to remove all of the detached particles, sedimentation occurs. Output from the sub-model consists of data on sediment yield and the particle-size distribution of the sediment.

Trials with the erosion sub-model using data from erosion experiments in Georgia and Iowa have shown that its predictive power on a storm-by-storm basis is superior to that of other models (Foster, Lane, Nowlin, Laflen and Young, 1980). Best results were achieved with data from Watershed P2, Watkinsville, Georgia, for which a correlation coefficient of $r = 0.79$ was obtained between predicted and observed soil losses for 32 storms in the period 1973-74 (Lane and Ferreira, 1980).

THE TEST DATA

The test data are taken from a field site near Silsoe in mid-Bedfordshire, England, where soil loss is being monitored on a storm-by-storm basis on a convexo-concave hillside with a maximum slope of 11°, on a bare sandy soil of the Cottenham Series, derived from the underlying sandstone strata of the Lower Greensand. Measurements at the site are part of a research programme on soil erosion in the U.K. (Morgan, 1980). Soil loss by rainsplash, overland flow and rill flow are investigated separately and in combination at three positions on the hillside: the upper convexity, the mid-slope and the lower concavity. The system of measurement, using field splash cups, sediment traps and volumetric determinations of rills on unbounded plots, is described elsewhere (Morgan, 1977).

The erosion sub-model is tested using data on soil loss by overland flow at the concave slope position for 33 storms in the period May 1973 to June 1979. The data include nine out of the ten most erosive storms in the period and six storms where no erosion occured. Storm loss values in the data set range from 0.0 to 26.3 t/ha.

MODEL STRATEGIES

The erosion sub-model is designed to operate for the case where soil loss by overland flow discharges into a channel at the foot of the slope, flowing at right angles to the hillslope direction. The sub-model can be extended to take account of the discharge from that channel either into a second channel, flowing at right-angles to the first, or into a pond or impoundment. The sub-model thus operates ideally for a typical runoff disposal system in a soil conservation scheme, comprising overland flow, a terrace channel and either a grass waterway or a tile-outlet drain. The sub-model cannot be readily applied, however, to the hillslope site in mid-Bedfordshire where the channel is in the form of a natural rill, running down the hillside, and where, as a result, the overland flow and channel flow paths are roughly parallel. No channel exists at the foot of the hillslope site in mid-Bedfordshire. Instead, the bottom of the slope is bounded by a hedge and bank, beyond which is a tar and gravel surfaced road.

The catchment area for the test data is taken as the width of two adjacent sediment traps (1 m) times the length of overland flow upslope of the concave slope position as observed in the field during storms. Within this catchment allowance is made for one naturally eroding channel or rill. Although the overland flow paths are approximately parallel to the channel flow path, some lateral movement occurs, particularly on the lower part of the slope (Fig. 1a).

Three strategies were considered for applying the sub-model to these conditions. The first strategy (Fig. 1b) was to operate with the field data and without any modifications to the structure of the sub-model. This is equivalent to placing the rill to run at right-angles to the hillslope at the foot of the test plot. This strategy assumes that all of the overland flow contributes to the rill which, given the flow arrangement described above, is unlikely. The second strategy was to maintain the position of the rill down the centre of the plot and to attempt to define an overland flow path at right-angles to the channel (Fig. 1c). This strategy is unrealistic because it implies that overland flow runs at right-angles to the hillslope direction and that it is possible to define lateral watersheds to the rill catchment and a representative overland flow length within the catchment for unconfined flow of ill-defined width. Using this strategy the length of the overland flow is extremely short and its slope is too gentle. When the sub-model is run in this way for storms where erosion is solely by overland flow, the soil loss is, not surprisingly, underpredicted. The third strategy was to operate the sub-model with the overland flow component at its full length and running downslope but to shorten the rill length, so that the overland flow contributes to only half the length instead of the full length of the channel (Fig. 1d). This strategy gives the same volume of overland

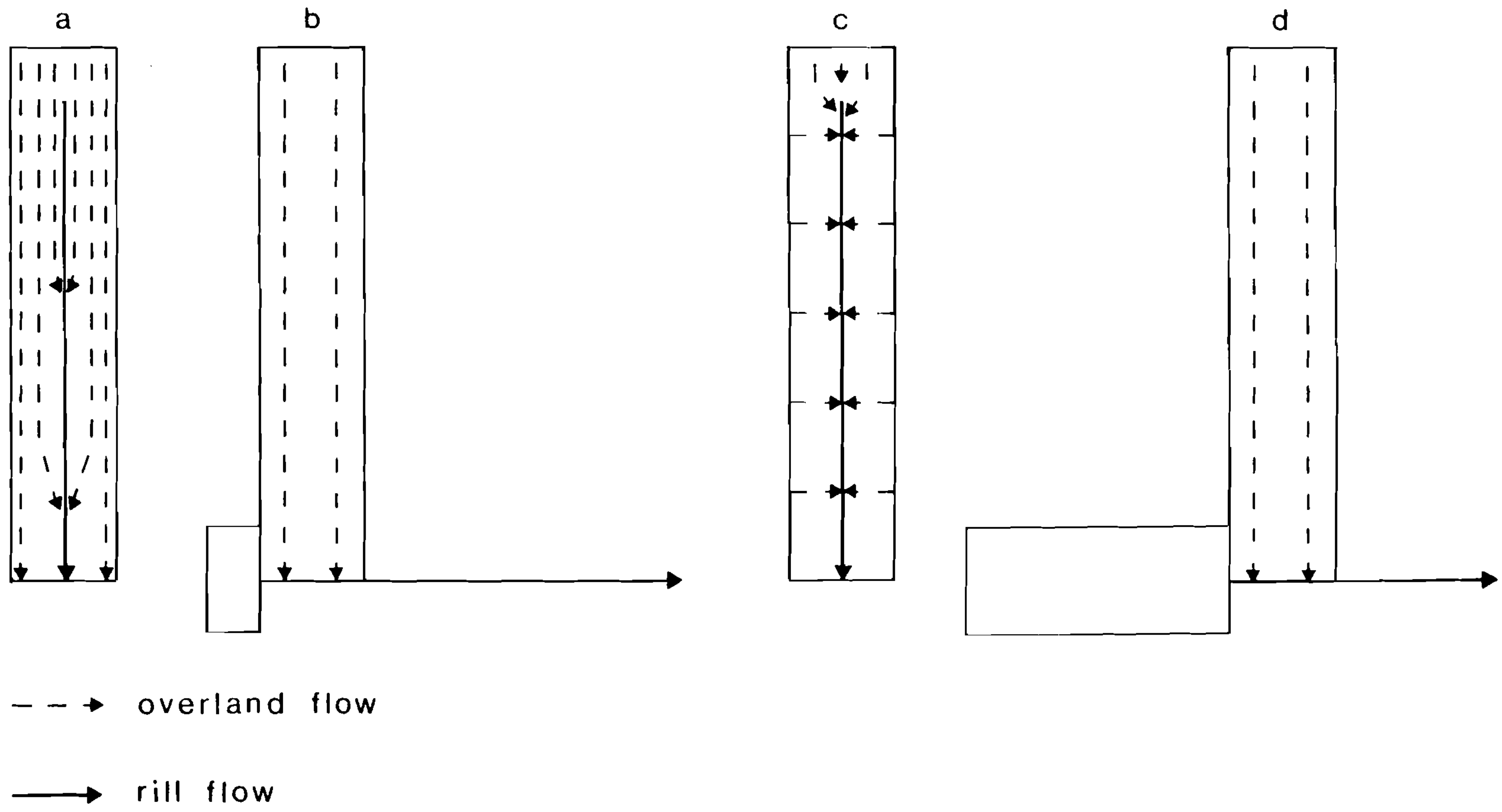

Figure 1. Paths of overland flow and rill flow (a) at the field site and (b), (c), and (d) in strategies used in applying the erosion sub-model. For explanation see text.

flow as the first strategy but, because it is concentrated in a shorter rill length, produces greater depths and velocities of rill flow and greater erosion potential. Not surprisingly, this strategy results in very high rates of rill erosion being predicted.

The best results are achieved with the first strategy and it is these which are presented here. The implications of using this strategy are discussed in a later section of the paper.

MODEL OPTIONS AND DATA INPUT

The erosion sub-model was tested using overland flow and channel components and with output on a storm-by-storm basis. Two data files are required for this test: a hydrology pass file and an erosion parameters file.

Table 1. Input parameters to the Hydrology Pass File

SDATE	Date of storm	Julian date
RNFALL	Volume of rainfall (in)	Observed data
RUNOFF	Volume of runoff (in)	Observed data
EXRAIN	Characteristic excess rainfall rate (in/h)	Estimated using unit hydrograph procedure (see text)
EI	EI_{30} index (American units)	Calculated from data on rainfall intensity derived from autographic rain gauge records

HYDROLOGY PASS FILE

The input to this file (Table 1) comprises the date of each storm (Julian date), the volume of rainfall, the volume of runoff, the characteristic excess rainfall rate and the value of the EI_{30} rainfall erosion index. Rainfall data are obtained from autographic rain gauge records at the meteorological station of the National Institute of Agricultural Engineering, 3 km from the field site. Runoff volumes are taken from field measurements. The characteristic excess or peak runoff rate is estimated by assuming, first, that overland flow during a storm follows a triangular hydrograph of the type shown in Figure 2, and second, that the time base (T) of that graph comprises that part of the storm where rainfall intensities exceed 10 mm/h (Morgan, in press).

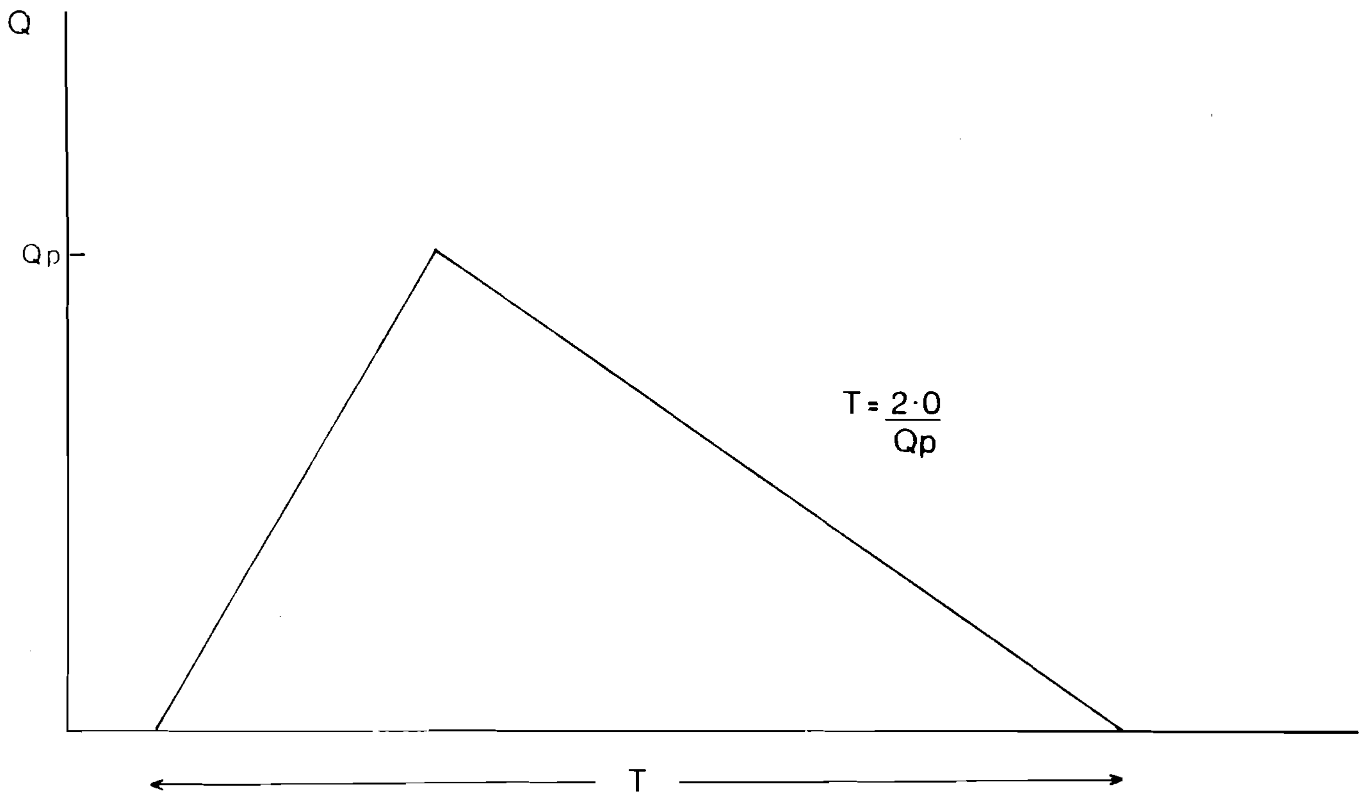

Figure 2. Unit (1 cm) hydrograph for overland flow runoff (Q) against time (T) used in the estimation of characteristic excess rainfall rate. For explanation, see text.
Qp = peak runoff.

The peak runoff rate (Qp) is calculated as 2.0/T for a 1-cm unit graph (Betson and Ardis, Jr. 1978) and this value is multiplied by Q/1 to give an estimated peak runoff rate for storm runoff volume Q (cm). EI_{30} values are determined by standard procedures taking data from autographic rain gauge charts (Wischmeier and Smith, 1978).

EROSION PARAMETERS FILE

The input to this file is listed in Table 2. Data on the grain-size distribution and organic content of the soil are derived from a laboratory analysis of field samples (Morgan, 1977). Slope profile data are based on field surveys with an Abney Level. Soil erodibility, expressed by the K-factor of the Universal Soil Loss Equation, was estimated using the nomograph of Wischmeier, Johnson and Cross (1971). A value of 0.23 was obtained for K but small arbitrary adjustments were made to give a different value for each of four segments of the hillside within the range 0.21 to 0.24. Conditions of crop management (C-factor), contouring (P-factor) and surface roughness (Manning's n)were assumed constant over the whole slope with respective values of 1.0, 1.0, and 0.2. The latter value for Manning's n is based on an analysis of the hydraulics of overland flow at the field site (Morgan, in press) although it is recognised that, in reality, the value will show both between storm (Morgan and Morgan, 1980) and within storm variation.

The catchment area has been defined above. The width and depth values assigned to the rill are based on field measurements. The water energy slope in the rill is assumed to equal the ground slope. A value of 0.02 is used for Manning's n in the channel, this being the value adopted for the design of channels in soil conservation systems, e.g. terrace channels, on unvegetated hillsides (Hudson, 1971). The critical shear stress for the soil in the channel is assigned a value of 0.06 lb/ft^2, this being the value recommended for earth channels with a low content of sediment in the water (Withers and Vipond, 1974).

RESULTS

Output from the sub-model separates the predictions of soil loss by overland flow from those by channel flow. When compared with the observed values the predictions for the overland flow component are too low for most storms whereas the predictions for the overland flow and channel flow components combined are too high for a few storms. Generally, when the observed soil loss values are low they are best predicted by the overland flow component but when they are high best predictions are obtained by summing the predicted soil losses for the overland flow and channel flow components.

Table 2: Input parameters to Erosion Parameters File

INITIAL PARAMETERS

SOLCLY	Fraction of clay in soil surface layer	Field data
SOLSLT	Fractions of silt in soil surface layer	Field data
SOLSND	Fraction of sand in soil surface layer	Field data
SOLORG	Fraction of organic matter in soil surface layer	Field data

OVERLAND FLOW PARAMETERS

DATOV	Area represented by overland flow profile (acres)	Field data. Plot width times observed length of overland flow
SLNGTH	Slope length of representative overland flow profile (ft)	Observed length of overland flow during storms
AVGSLP	Average slope of representative overland flow profile (ft/ft)	Field measurement
SB	Slope at upper end of profile	Field measurement
SM	Slope at mid-section of profile	Field measurement
SE	Slope at lower end of profile	Field measurement
XIN(3)	Distance from top of slope where mid-slope uniform section begins (ft)	Field measurement

Table 2 continued

YIN(3)	Elevation above lowest point where mid-slope uniform section begins (ft)	Field measurement
XIN(4)	Distance from top of slope where mid-slope uniform section ends (ft)	Field measurement
YIN(4)	Elevation above lowest point where mid-slope uniform section ends (ft)	Field measurement
NK	Number of slope segments differentiated by changes in soil erodibility factor	Four segments selected based on changes in slope angle
XKIN(1)	Relative horizontal distances (distance/ slope length) from top of slope to bottom of each segment differentiated by soil erodibility	Field measurement
KIN(1)	Soil erodibility factor for each slope segment (tons/acre/EI_{30})	Erodibility (K) value for mid-slope uniform segment estimated from nomograph (Wischmeier, Johnson and Cross, 1971); small arbitrary changes made in this value to give values for remaining segments.
CHANNEL FLOW PARAMETERS		
NS	Number of channel segments differentiated by changes in slope	Three segments selected based on differences in channel gradient

Table 2: continued

FLAGC	Channel shape	Naturally eroded channel
FLAGS	Friction slope (energy grade line)	Assumed equal to channel slope
CONTL	Control of depth in outlet channel	Uniform flow selected as control. In reality there is no outlet to the channel which ends in a sediment fan.
LNGHT	Channel length (ft)	Field data
DATCH	Total drainage area of channel at lower end of channel (acres)	Field data. Plot width times slope length.
DAUCH	Drainage area above upper end of channel (acres)	Field data. Plot width times distance from top of slope to point where channel begins
Z	Side slope of channel cross-section (horiz/vert)	Typical field value
TX(1)	Distance from lower end of channel to bottom of each channel segment (ft)	Field data
TS(1)	Slope of each segment	Field data

UPDATEABLE INITIAL PARAMETERS

PDATE	First date that updateable parameters are valid	Julian date
CDATE	Last date that updateable parameters are valid	Julian date

Table 2: continued

UPDATEABLE OVERLAND FLOW PARAMETERS

NC, NP, NM	Number of slope segments differentiated by changes in crop management factor (C), contouring factor (P) and Manning's n (M) respectively	One segment. Values assumed constant over whole slope
XCIN(1), XPIN(1), XMIN(1)	Relative horizontal distance from top of slope to bottom of each segment where C, P and n values respectively are differentiated	XCIN(1), XPIN(1) and XMIN(1) equal 1.0. Only one segment differentiated
CIN	Crop management factor (C)	Bare soil CIN = 1.0
PIN	Contouring factor (P)	No contouring. PIN=1.0
MIN	Manning's n value	n = 0.2 for overland flow (Morgan, in press)

UPDATEABLE CHANNEL FLOW PARAMETERS

NN, NCR, NCV, NDN, NDS, NW	Number of channel segments differentiated by changes in Manning's n (N), critical shear stress (CR), shear stress for cover (CV), depth to non-erodible layer in channel middle (DN), depth to non-erodible layer at channel sides (DS) and changes in channel width (W) respectively.	One segment. Values assumed constant along whole channel
XN, XCR, XCV, XDN, XDS, XW	Distance from lower end of channel to bottom end of each segment where values of N, CR, CV, DN, DS and W are differentiated (ft)	Values = 0 ft. One segment only.

Table 2: continued

TN	Manning's n for channel	n = 0.02 for channel flow (Hudson, 1971)
TCR	Critical shear stress for soil of channel	0.06 lb/ft^2 (Withers and Vipond, 1974)
TCV	Shear stress for cover stability for channel	Values of 100 assigned. Cover failure not allowed (Knisel, 1980. p.250)
TDN, TDS	Depth to the non-erodible layer in middle and at sides of channel respectively (ft)	0.5 ft selected as typical maximum depth of channels
TW	Width of channel (ft)	Typical field value. TW = 1 ft.

For further analysis it was decided to set an arbitrary threshold of storm soil loss of 1 t/ha. Where the observed soil loss is less than the threshold value, the overland flow component of the sub-model is used to provide the predicted soil loss value. Where the observed soil loss equals or exceeds the threshold value, the overland flow and channel flow components are combined to give the predicted value.

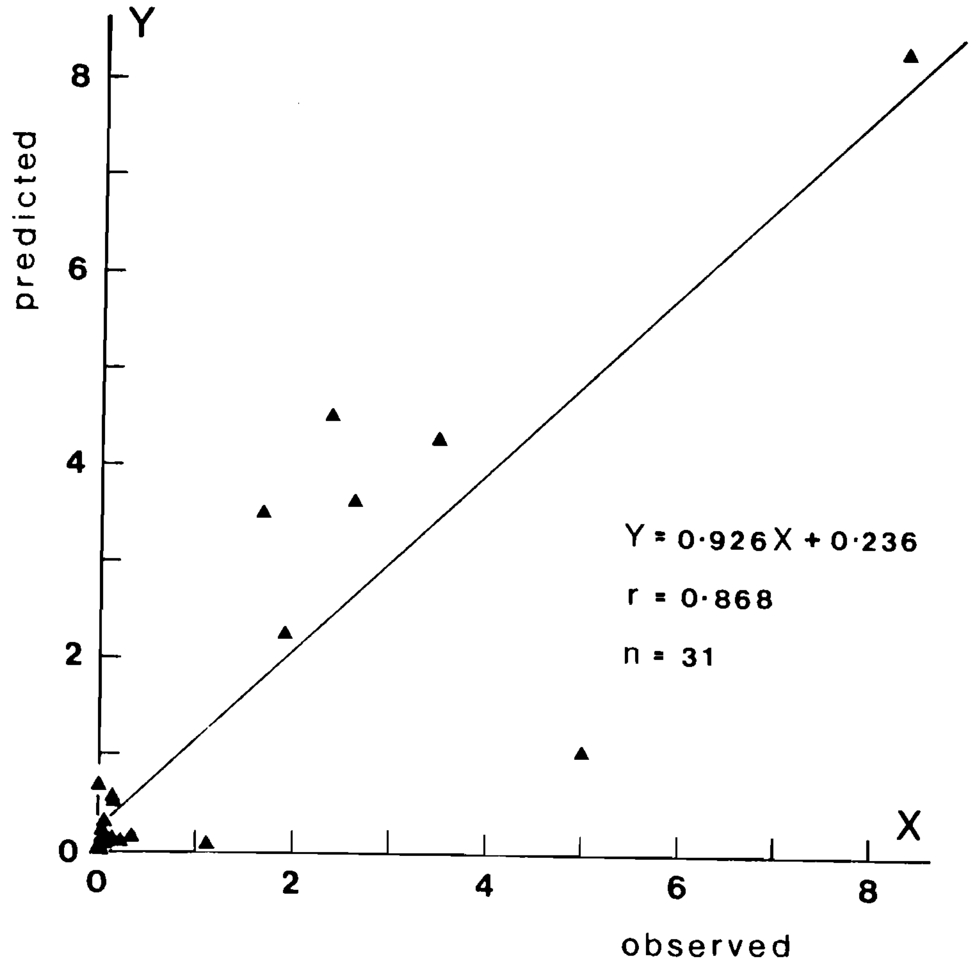

Figure 3. Plot of predicted against observed soil loss (t/ha).

When the predicted values are derived in this way there is a significant correlation between them and the observed values ($r = 0.87$; $n = 31$; $P > 0.001$; Fig. 3). In calculating the correlation coefficient, two storms have been omitted where the predictions are poor. In the case of the storm on July 6 1973 the observed soil loss value of 8.3 t/ha is only an estimate because of the washing away of part of the measuring equipment and the estimate may well be too low. The predicted value is 30.5 t/ha. For the storm on 7 August 1978, the measured soil loss is exceptionally high at 26.3 t/ha and it is likely that the observed runoff value, used as input to the soil loss prediction of 1.1 t/ha, is too low. With excessive silting of the sediment traps, associated with high soil loss, runoff would have been prevented from entering them. For the remaining 31 storms the slope of the best fit linear regression line between predicted and observed values is close to one at 0.926 (Fig. 3).

DISCUSSIONS

The results of this trial of the CREAMS erosion sub-model, using field data from 31 storms in mid-Bedfordshire, are promising. First, the correlation coefficient between predicted and observed values of soil loss compares well with the best value achieved with similar trials using data from the U.S.A. (Lane and Ferreira, 1980). Second, as also indicated by the trials with data from the U.S.A., the sub-model gives results which are as good as or superior to those achieved by other models. In this case the results may be compared with those obtained with a best fit linear regression equation relating soil loss to rainfall and runoff energies ($r = 0.82$; $n = 30$; Morgan, 1979) and those obtained using a sediment transport equation specially derived for overland flow ($r = 0.69$; $n = 30$; Morgan, in press). Third, the slope of the regression line between the predicted and observed values is sufficiently close to one as to indicate a one-to-one relationship, i.e. that the sub-model predicts values that closely approximate the observed values and which require no further adjustment by some empirically derived constant or correction factor.

Although it may be argued that the predicted soil loss values used in the statistical analysis have been arbitrarily contrived through the operation of the threshold to determine whether the value from the overland flow component or that from the overland and channel flow components combined is used, in reality, the threshold procedure has some interesting implications for the understanding of how erosion by overland flow operates in the field. It has been inferred from the analysis of the data collected at the site that raindrop impact is the main agent of detachment and overland flow the main agent of transport (Morgan, 1977). The average hydraulic conditions of overland flow are ones of low Reynolds and low Froude numbers with the flow being essentially laminar but disturbed by raindrop impact (Morgan, in press). During storms of low intensity, few soil particles are detached, there is little runoff, little sediment transport and soil loss is virtually zero. During storms of high intensity, rates of soil detachment by rainsplash are high and field observations show that, even if rills are not formed, overland flow follows an anastomosing pattern with localised concentrations of water where flow depths and velocities are increased. It is presumably these local increases that raise the transport capacity of the flow. As a result of testing the CREAMS erosion sub-model, it becomes necessary to question whether these flow concentrations should be regarded as part of the overland flow or whether they should be treated as channels, albeit incipient ones. Further research on this question will complement that being carried out elsewhere on the formation of rills, in particular that on the changes that occur in the hydraulic properties of overland flow as rills are initiated (Savat, 1979).

Viewing the overland flow concentrations as incipient channels implies that virtually all overland flow contributes to them. This may explain why the best results are obtained when the sub-model is operated in accordance with the first strategy (Fig. 1b). Although, as indicated earlier, the conditions represented by the first strategy and the field conditions (Fig. 1a) appear, at first sight, to be very different, in fact, they may not be so dissimilar. Although the lateral transfer of overland flow to the channel takes place over a range of overland flow distances, because the paths of the overland flow and rill flow are roughly parallel, most of the transfer occurs on the lower part of the slope. The dominant overland flow length is thus reasonably well approximated by the average of the maximum lengths of overland flow observed in the field over a range of storms. Thus, adopting this latter parameter as the representative length of the overland flow profile and operating the sub-model according to the first strategy, results in a simulation that is reasonably close to field conditions. This is particularly the case if, as implied above, the channel is not well-defined and represents only a path of flow convergence within the overland flow.

CONCLUSIONS

This preliminary test of the applicability of the CREAMS erosion sub-model to British conditions has proved sufficiently encouraging to warrant further work. For the small sample of 31 storms a significant correlation is obtained between the predicted and observed values of soil loss. The sub-model now needs to be tested using a full range of data from mid-Bedfordshire. This covers the period 1973-79 and comprises soil loss measurements for bare ground, grassland, cereals and woodland, on loamy sand, clay and chalk soils, for slopes from 3^{o} to 11^{o}. A similar data base exists on which to test the CREAMS hydrology sub-model for predicting runoff.

By carrying out this further work, the suitability of the CREAMS model for assessing non-point source pollution in the U.K. will become apparent. From this it should be clear whether, in order to evaluate the problem of non-point source pollution, effort should be directed at transferring the CREAMS model to the U.K. rather than concentrating research on the development of alternative modelling procedures. In addition, as seen above for the case of rill formation, the work will highlight areas where more basic research is required and this, in turn, will lead to further improvements in the CREAMS model.

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REFERENCES

Betson, R.P. and Ardis, C.V. Jr. 1978. Implications for modelling surface-water hydrology. In Kirkby, M.J. (ed), Hillslope Hydrology, Chichester, John Wiley, 295-323.

Department of the Environment, 1973. A background to water reorganization in England and Wales. London, HMSO.

Foster, G.R., Lane, L.J., Nowlin, J.D., Laflen, J.M. and Young, R.A. 1980. A model to estimate sediment yield from field-sized areas: development of model. In Knisel, W.G. (ed), CREAMS: A field-scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Report No. 26, 36-64.

Foster, G.R. and Meyer, L.D. 1972. A closed form soil erosion equation for upland areas. In Shen, H.W. (ed), Sedimentation. Fort Collins, Colorado State University, 12. 1-12.19.

Hudson, N.W. 1971. Soil Conservation. London, Batsford.

Knisel, W.G. Jr. 1978. A system of models for evaluating non-point-source pollution: an overview. IIASA Publication CP-78-11, Laxenburg.

Knisel, W.G. Jr. 1980. CREAMS: A field-scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Report No. 26.

Lane, L.J. and Ferreira, V.A. 1980 Sensitivity analysis. In Knisel, W.G. (ed), CREAMS: A field-scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Report No. 26, 113-15[illegible].

Meyer, L.D., Foster, G.R. and Römkens, M.J.M. 1975 Source of soil eroded by water from upland slopes. In Present and prospective technology for predicting sediment yields and sources. USDA Agr. Res. Service Pub. ARS-S-40, 177-189.

Meyer, L.D. and Wischmeier, W.H. 1969. Mathematical simulation of the process of soil erosion by water. Trans. Am. Soc. Agr. Engnrs. 12, 754-758, 762.

Morgan, R.P.C. 1977. Soil erosion in the United Kingdom: field studies in the Silsoe area, 1973-75. Nat. Coll. Agr. Engng. Occasional Paper No. 4, Silsoe.

Morgan, R.P.C. 1979 Recherches sur l'érosion des sols sableux en Bedfordshire, Angleterre. Proceedings, Seminar on Agricultural soil erosion in temperate non-Mediterranean climate. Université Louis Pasteur, Strasbourg, 35-38.

Morgan, R.P.C. 1980. Soil erosion and conservation in Britain. Progress in Physical Geography, 4(1), 24-47.

Morgan, R.P.C. in press. Field studies of sediment transport by overland flow. Earth Surface Processes.

Morgan, R.P.C. and Morgan, D.D.V. 1980. Problems of validating a Meyer-Wischmeier type soil erosion model with field data. In Morgan, R.P.C. (ed), Soil Conservation: problems and prospects. To be published by John Wiley, Chichester, 327-334.

Savat, J. 1979. Laboratory experiments on erosion and deposition of loess by laminar sheet flow and turbulent rill flow. Proceedings, Seminar on Agricultural soil erosion in temperate non-Mediterranean climate. Université Louis Pasteur, Strasbourg, 139-143.

Wischmeier, W.H. and Smith, D.D. 1978. Predicting rainfall erosion losses. USDA Agricultural Handbook No. 537.

Wischmeier, W.H., Johnson, C.B. and Cross, B.V. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil and Wat. Conserv. 26, 189-193.

Withers, B. and Vipond, S. 1974. Irrigation: design and practice. London, Batsford.